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Slurry Erosion of Al_2O_3-SiO_2/Al-4Mg Metal Matrix Composites

by

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Abstract

The purpose of this study was oriented toward the understanding of wear mechanisms occurring when a slurry impinges on a metal matrix composite. The effects of incidence angle and particle velocity were investigated. The composite material consisted of Kaowool fiber (47% Al_2O_3 - 53% SiO_2) disc-shaped preform impregnated with an aluminum alloy containing 4% magnesium. The fibers in the preform are randomly oriented in a plane perpendicular to the disc axis. The different types of preform used gave composites with 10, 15 and 20% volume fraction of fibers. The samples were made by squeeze-casting under a pressure of 80 MPa. The slurry erosion tests were continued for a period of 15 minutes in order to obtain significant mass losses. The results show an increase in mass loss associated with an increase of particle velocity. Also, the mass loss increases when the incidence angle increases until an angle of nearly 30° is reached. For incidence angle over 30°, the behavior is not simple and is not the same for the different velocities tested. When the fiber volume fraction increases, the wear resistance is slightly improved. Observations with a scanning electron microscope reveal fiber breakage on the eroded surface.

THE GOAL OF THIS STUDY was to evaluate the improvement in the erosion wear resistance of an aluminum alloy by adding ceramic fibers as a reinforcement. Some results have been reported on the dry erosion of silicon carbide whisker reinforced alumina [1] and silicon nitride [2]. The behaviors of these ceramic matrix composites were very different: a substantial improvement in the erosion resistance for the first one and a lack of reinforcement effect on erosion resistance in the second case. For the metal matrix composites (MMC's) reinforced with hard particles, the degradation of the composites increases as the fraction of hard particles increases [3]. These few results illustrate well that the study of the erosion of composite materials is complex and strongly dependent on the material tested.

In the slurry erosion testing, the velocity of the slurry and its incidence angle on the surface of the material are two important parameters. The behavior of the reinforcing fibers was investigated through these two parameters.

EXPERIMENTAL PROCEDURE

FABRICATION OF MMC'S - The samples were made by infiltrating a preform with an aluminum alloy by squeeze casting technology. The 25.4 mm diameter disc-shaped preform consisted of Kaowool fiber (47% Al_2O_3 - 53% SiO_2) randomly oriented in a plane perpendicular to the disc axis. The preform was located in the center of a cylindrical die having a diameter of 38.1 mm. The die was heated to a temperature of 300°C. The aluminum alloy (SAE 5083) contained nearly 4% of magnesium which is well known to facilitate the wetting of the fiber by the alloy. After melting, the alloy was superheated to a temperature of 810°C and then poured into the die over the preform. The ram was inserted rapidly in the die to obtain the maximum pressure of 80 MPa within 0.5 second. The load was maintained for 10 seconds in order to complete the rapid solidification process. The high pressure during solidification permits the molten alloy to impregnate the preform and to eliminate porosity. The thickness of the samples was variable (depending on the amount of alloy poured in the die) with a mean of 10 mm. The composite fabrication steps are shown in Figure 1.

Three types of preform were used leading to fiber volume fractions of 10, 15 and 20%.

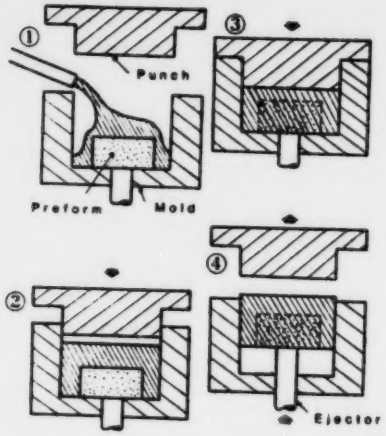


Fig. 1 - Fabrication of metal matrix composites: 1- Pouring the alloy over the preform in the mold. 2- Closure of the heated chamber. 3- Impregnation of the preform. 4- Ejection of the solidified composite out of the mold.

Optical micrographs of the different MMC samples are shown in Figure 2. The density of the alloy is nearly 2.64 g/cm^3 and that of the Kaowool fibers is 2.6 g/cm^3. The resulting densities of the different composites is then nearly the same, independent of the fiber volume fraction.

EROSION TESTING - Erosion tests were performed on an erosion apparatus based on an air-powered double-diaphragm slurry pump. The slurry was pumped from a tank containing about 7 l of slurry with a silica sand concentration of 10% by wt. The size distribution of sand particles lay between 200 and 300 µm. The pumped slurry was projected against the surface of the sample and returned to the tank. The velocity of the erodent particles has been assumed equal to the velocity of the slurry jet (having a diameter of 4.76 mm) because the sand concentration was high enough to justify this approximation. The velocity of the slurry was measured by an electromagnetic flowmeter. Tests were made with slurry velocities of 12.5 and 17 m/s. The sample holder permitted the incidence angle of the jet to be set at 15 to 90°. The erosion apparatus is shown schematically in Figure 3.

The slurry erosion tests were continued for a period of 15 minutes in order to obtain significant mass losses of the samples. The erosion wear values correspond to these mass losses. The comparison of wear values can be made from one sample to another because, as mentioned before, the density of the different types of sample is the same. Before and after the erosion tests, the samples were cleaned in

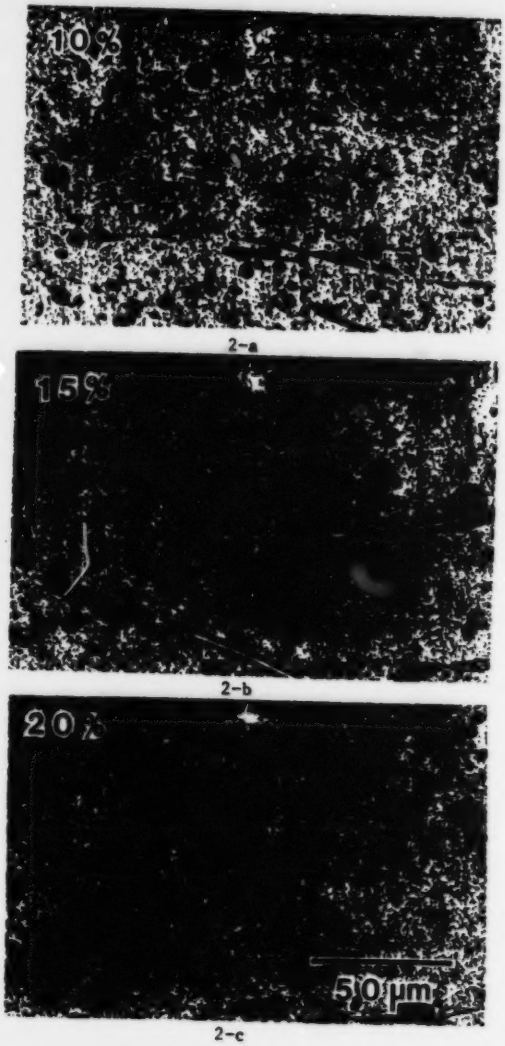


Fig. 2 - Microstructures of the metal matrix composites with a) 10%, b) 15% and c) 20% of Kaowool fibers (optical microscopy).

an ultrasonic bath, dried and weighed.

SCANNING ELECTRON MICROSCOPE OBSERVATION Some eroded surfaces were observed in the scanning electron microscope (SEM). A thin coating of Au-Pd was deposited on the surface to reduce the accumulation of charge by the non-conductor fibers. Also, some samples were cut perpendicularly to the eroded surface in order to observe the behavior of fibers under the worn surface. After the erosion tests, it was difficult to observe the fibers on the worn surfaces because the deformed aluminum alloy covered them. It was necessary to etch

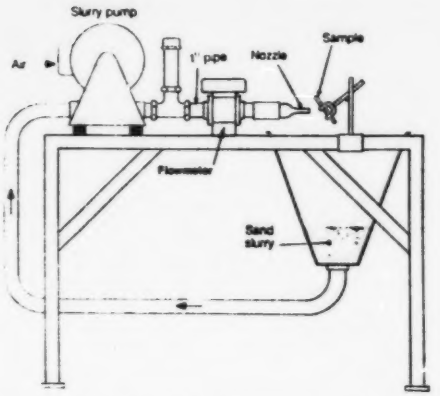


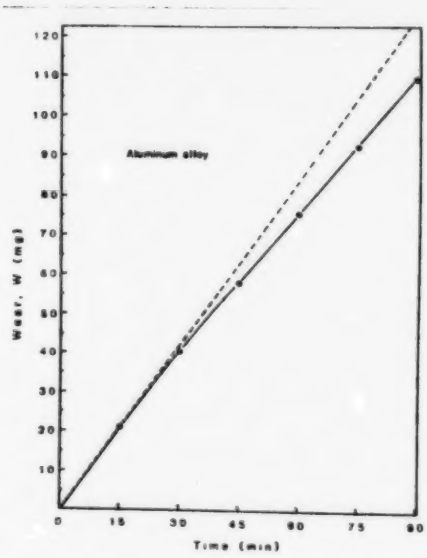
Fig. 3 - Experimental apparatus used for the erosion tests.

the worn surface in order to observe the damage to the fibers. A solution of 10 ml of hydrofluoric acid, 15 ml of hydrochloric acid and 90 ml of water was used.

RESULTS

SAND DEGRADATION - Sand degradation occurs after a certain period of time because the slurry is continuously recirculated in the closed-loop system. With the same batch of slurry, six tests were made for a total of 90 minutes sand use duration. The mass loss as a function of time is plotted in Figure 4 for the alloy and for the composite containing 20% by vol. of fibers. The sand degradation during the first 15 minutes is assumed to be negligible and then the theoretical straight line corresponding to constant erosion rate is computed from the point related to the measurement after 15 minutes and the origin. The degradation seems to begin being important after 30 minutes for the composite and 45 minutes for the alloy. After 45 minutes, for both materials, the erosion rate (slope of the curve) becomes constant and a straight line fits the experimental measurements. This suggests that after 30 or 45 minutes, there is no further sand degradation.

From the curves of Figure 4, one can define a correction factor which takes into account the sand degradation. The correction factor is defined as the theoretical mass loss divided by the experimentally measured mass loss for a given time. The wear value for a given sample will then be corrected by multiplying the experimental loss with the correction factor corresponding to the age of sand for the given sample. One should note that the correction factor is nearly the same for the aluminum alloy and the composite. Effectively, for a test duration of 90 minutes, the correction factor is 1.14 for the alloy and 1.16 for the composite with 20% by vol. of fibers. The curves on Figure 4 were obtained for an incidence angle of 90° but it was verified that the correction factor is the same for the other incidence angles.



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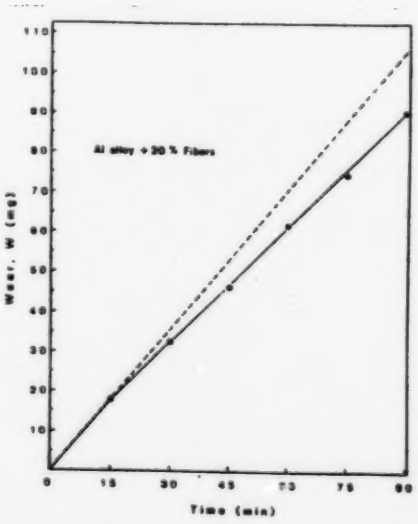


4-b

Fig. 4 - Erosion wear versus time a) for the Al-4%Mg alloy and b) for the composite containing 20% by vol. of fibers.

EFFECTS OF PARTICLE VELOCITY AND INCIDENCE ANGLE - The wear as a function of incidence angle is reported in Figure 5 for the two particle velocities tested. As an indication, the erosion for pure aluminum for the same experimental conditions is proportional to the velocity to the power 4 (Fig. 6). A broad band of data points represents the behavior instead of a curve for each type of material because the variation of experimental conditions causes some anomalies. Nevertheless, the tendency shown indicates that as the fiber content increases, the wear resistance also increases slightly. Also, there is a significant decrease of the mass loss when the particle velocity is reduced from 17 to 12.5 m/s. By taking the limiting values of the envelopes (Fig. 5) for the incidence angle of 90°, the calculated velocity exponent in the relation $W = Kv^n$ is equal to 4.4 for the upper and lower limits.

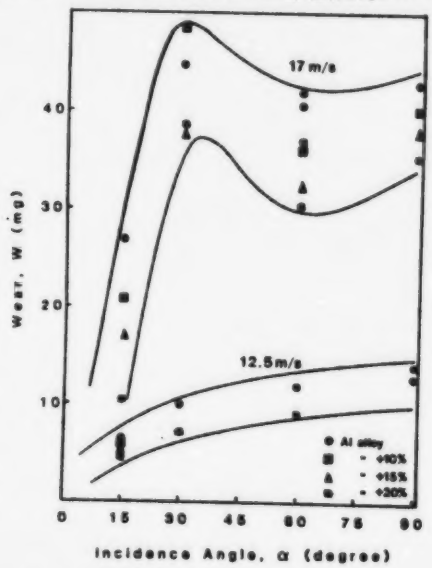


Fig. 5 - Effect of incidence angle and particle velocity on the erosion wear.

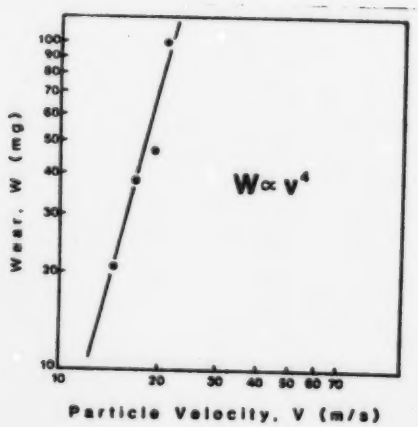


Fig. 6 - Erosion wear (W) of pure aluminum as a function of particle velocity (V). Test duration: 15 min, incidence angle: 90°.

EFFECT OF FIBER VOLUME FRACTION - An increase in fiber volume fraction resulted in an improvement of wear resistance (inverse of wear value). The wear values for a velocity of 17 m/s as a function of fiber volume fraction are reported in the graph of Figure 7. For each incidence angle, there is a straight line which fits the results, except for the angle of 30°. The scatter of results is significant around the maximum of erosion wear related to the incidence angle of 30°.

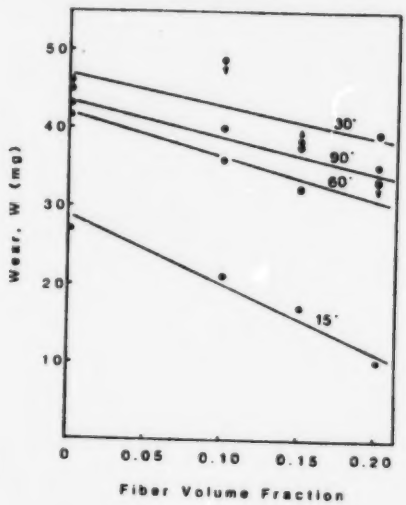
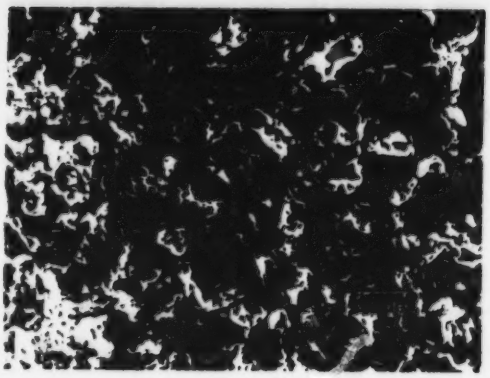


Fig. 7 - Erosion wear as a function of fiber volume fraction for a particle velocity of 17 m/s.

SEM OBSERVATIONS - The observation of worn sample surfaces revealed mostly the erosion characteristics of ductile materials such as platelet formation and elongated craters for small incidence angles. Figure 8 shows micrographs of some samples eroded with different experimental conditions. From these micrographs, it is impossible to distinguish between the samples having 15 and 20% by vol. of fibers. The samples eroded by particles having a velocity of 12.5 m/s look similar to the ones eroded with higher particle velocity. Also, almost no fibers are entirely visible at the surface.

Following etching of the worn surface, the fibers at the surface lost the thin layer of deformed aluminum alloy which was displaced



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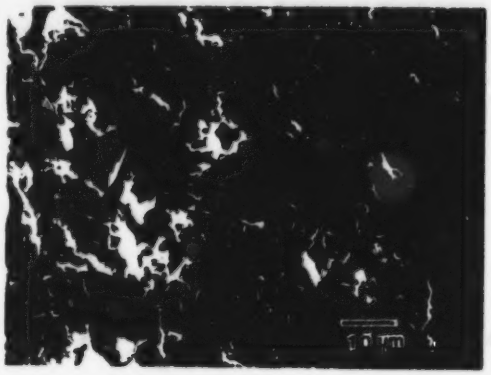

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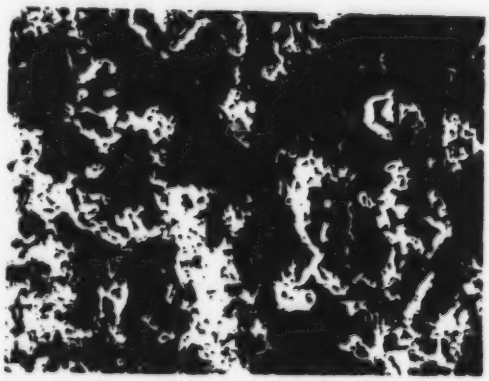
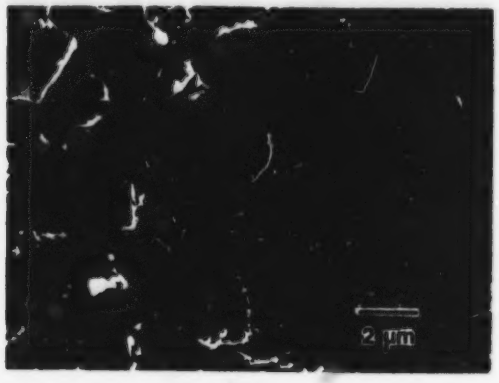


8-c

Fig. 8 - Eroded surfaces for different test conditions: a) 15% by vol. of fibers, V = 17 m/s; b) Al alloy, V = 17 m/s; c) 20% by vol. of fiber, V = 12.5 m/s.

over the fibers during the erosion process. For the samples eroded with a particle velocity of 17 m/s, the fibers were typically broken into small pieces as shown in Figure 9-a. Fiber breakage also occurred for a particle velocity of 12.5 m/s but to a much lesser extent. Unbroken fibers in this case often were observed (Fig. 9-b).

Some samples were observed in a view perpendicular to the worn surface. Figure 10 shows that fiber breakage occurred only at the surface. In our observations, no fiber degradation under the worn surface was seen. The depth of the damage seemed to be within 5 μm.



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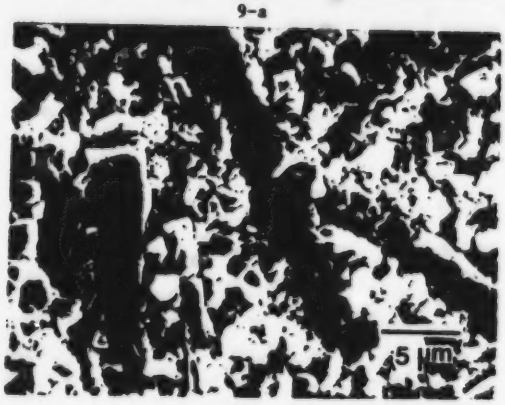

9-b

Fig. 9 - Worn surfaces after etching. Samples with 20% by vol. of fibers eroded with particle velocities of a) 17 m/s and b) 12.5 m/s. α = 90°.

DISCUSSION

The description of the wear mechanism as a function of the incidence angle is not simple from a microscopical point of view. Even if the incidence angle is experimentally held constant, the slurry flow near the

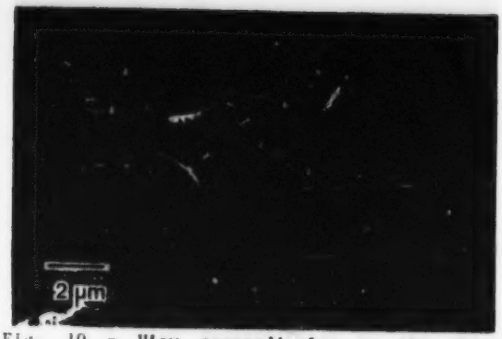

Fig. 10 - View perpendicular to the worn surface of a composite containing 15% by vol. of fibers (after etching). No damage occurred under the worn surface.

surface brings a distribution of incidence angles [4]. The erosion spot is then the result of many impacts under different angles. For a given point of the worn surface, it is very difficult to assign a precise incidence angle. Nevertheless, it is possible to relate macroscopically the wear and the incidence angle. The maximum of the curve shown in Figure 5 for a particle velocity of 17 m/s falls around an incidence angle of 30°. For ductile materials, it is well known that the maximum in erosion for a small angle is related to a maximum in the efficiency of the microcutting mechanism [5]. The maximum is not well pronounced because the sand particles are quite round with the result that the microcutting mechanism is a weak component of the overall mechanism. For a particle velocity of 12.5 m/s, there is no maximum probably because the kinetic energy of particles is too low to permit microcutting. The eroded surfaces for the aluminum alloy and for the composites are similar (Fig. 8) and show, instead of microcutting, many platelets associated with intense plastic deformation of the alloy. The wear mechanism observed is of the same type as the one described by Levy [6].

It was observed that the breaking of fibers is much more important for a particle velocity of 17 m/s than for a velocity of 12.5 m/s (Fig. 9). This is probably due to a velocity threshold under which the breakage of fibers occurs rarely. Because the reduction in wear associated with the decrease of the sand particle velocity is similar for the alloy and for the composites, it is assumed that the erosion wear of the composites is controlled by the wear of the matrix. Effectively, a coarse evaluation of the velocity exponent gives a value of nearly 4.4 for the alloy and the composites. The fact that the fibers are broken for the higher particle velocity does not result necessarily in an acceleration of the wear process. As it is shown in Figure 9, even after etching the broken fibers remain bonded to the surface. To detach the fibers from the surface, the surrounding matrix has to be eroded, whether the fibers are broken or not. This again suggests that the erosion wear of composites is controlled by the erosion of the matrix which supports the fibers. Also, even for a particle velocity of 17 m/s, fiber damage does not occur under the surface (Fig. 10). The absence of degradation under the surface brings a better wear resistance because the subsequent layers that will be exposed to the slurry will not be weakened.

In spite of the fact that the curves of Figure 7 are quite linear, the rule of mixtures relating the wear resistance (defined as the inverse of the wear) and the fiber volume fraction cannot be applied in the present case. The application of the rule of mixtures is valid if the wear resistances of the two constituents are similar and if the wear processes of the constituents are independent. The intimate contact between the fiber and the matrix leads to a region at the interface where the wear mechanism is neither that of the matrix nor that of the fiber. Moreover the wear mechanisms of the ductile matrix and the brittle fiber are completely different. Figure 11 presents the wear resistance as a function of the fiber volume fraction. For an incidence angle of 15°, the wear resistance seems more improved than for the other incidence angles by a small increase of fiber volume fraction. For the larger incidence angles, the small additions of fiber in our investigation did not improve the wear resistance significantly. However for an incidence angle of 15°, the wear resistance was considerably increased for all fiber volume fractions. The protection of the matrix by the fibers for an angle of 15° can be explained by the fact that one side of the fiber undergoes more numerous impacts than the hidden side. This sheltering effect brought by the fiber leads to a more efficient support of the fiber. The protection brought by fibers lying parallel to the exposed surfaces is greater for a small incidence angle.

SUMMARY

From this study on the erosion of MMC's, some points arise that help to elucidate the wear mechanisms occurring at the surface:

- The wear of the matrix is associated with platelet formation due to intense plastic deformation of the surface layer.
- Even if the fibers are broken at the surface, they remain attached to the surface with the help of the matrix supporting the fibers. The breakage of fibers does not result directly in mass loss.
- The damage under the surface layer is not significant.
- The wear resistance is slightly ameliorated by an increase of fiber volume fraction except for an incidence angle of 15° where

the wear resistance is improved significantly.

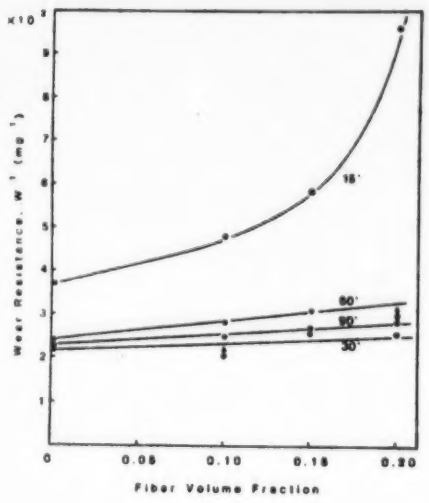

Fig. 11 - Wear resistance (inverse of mass loss) as a function of fiber volume fraction.

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